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A Headway Control Algorithm for ACC Vehicles with the Compensation of the Preceding Vehicle Acceleration

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Abstract

A headway control algorithm with the compensation of the preceding vehicle acceleration is proposed. Multi performances such as driving safety, passenger comfort and energy economy are considered to imitate car-following features of skilled drivers. To follow the preceding vehicle more stably and safely, the preceding vehicle acceleration is estimated via a differential tracker and a feedforward term with the input of estimated acceleration is added into the headway controller with a feedback term. The feedforward and feedback headway controller is designed via quadratic boundedness concept and the multi performances are coordinated by transforming the ranges of them into linear matrix inequalities. Finally, the car-following performance of the designed algorithm is verified under operating conditions in which the preceding vehicle speed is constant or changing.

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Keywords: Adaptive cruise control(ACC); Headway Control; coordination; Control constraint; Quadratic boundedness

1. Introduction

Adaptive cruise control (ACC) systems regulate autonomously the longitudinal velocity of vehicles, based on the traditional cruise control systems, according to the inter-vehicle kinematic between the host vehicle and the preceding one and maintain a safe inter-vehicle distance between them [1]. With the development of automotive active safety technologies, ACC has become the focus from international automotive safety field. Early studies focused almost on the determination of a safe inter-vehicle distance based on automotive inherent performance of throttle/brake dynamics [2]. As the study goes deep, several related and

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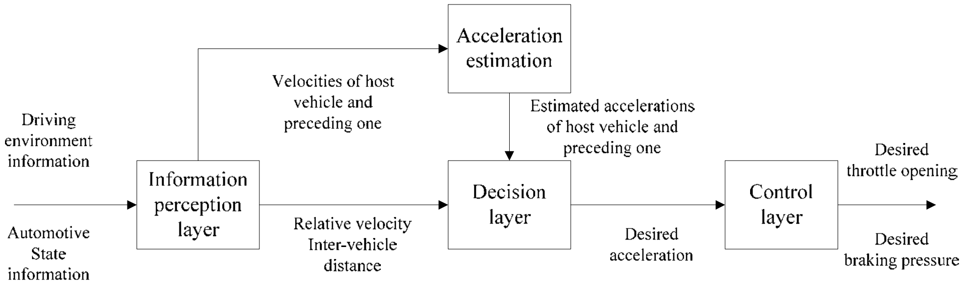


Fig. 1: The overall block diagram of ACC

contradicted performance indicators, such as driving safety, passenger comfort and energy economy, are considered in the multi-objective decision techniques to maintain a desired inter-vehicle distance [2]. Recently, the trend of ACC is the coordination of multi performance indicators via Model Predictive Control (MPC), Thus, the multi-objective decision is transformed into the multi-objective coordination control. Vibhor et al. had designed the headway control algorithm for transitional maneuvers using MPC [3]. The safety and comfort were satisfied by setting the control and state constraints. Li et al. had designed a headway control algorithm for steady following [4]. The algorithm coordinated the energy economy, following performance and drivers' desired response. However, for the complex computation of MPC, the computation time of MPC may exceed the sample time of ACC at every sample time. This leads to deterioration of ACC. Other improved MPC technologies had been also applied. Naus et al. had designed an explicit MPC algorithm for ACC. The computation time has been reduced via solving off-line optimization algorithm and table look-up on-line [5]. The external disturbance of MPC-oriented model is assumed to be measurable and constant in existing literatures. However, the preceding vehicle acceleration is not measurable via existing on-board sensors and should explicitly be considered in the design of headway control algorithm to improve the car-following performance.

The starting point of ACC is to assist and/or to replace drivers to maintain a safe inter-vehicle distance. How to apply and simulate a skilled driver's car-following behaviour is an effective technical way of high passenger acceptability. In existing literatures, the influence of the preceding vehicle acceleration on following performance has not been adequately studied. Considering the preceding vehicle acceleration in the design of headway control algorithm could simulate the foreseeability of drivers. This is important to inter-vehicle safety. Furthermore, The performance indicators representing following behaviour, such as driving safety, passenger comfort and energy economy, are related and contradicted to some extent and could be coordinated to simulate drivers' following behaviour.

In this manuscript, based on the early study on drivers' velocity control behaviour [6], a feedforward and feedback control technology is applied to coordinate the multi performance indicators via quadratic boundedness concept. In Section 2, an inter-vehicle kinematic model is established based on the constant time gap policy and the multi performance indicators are represented with the states and control input. In Section 3, the feedforward and feedback headway control algorithm is designed via quadratic boundedness concept to compute the desired acceleration. In Section 4, the computer simulations are carried out to verify the designed algorithm. Section 5 concludes the manuscript.

2. Problem formulation

As shown in Figure 1, an ACC system generally contains an information perception layer, a decision layer and a control layer. The information perception layer gains the status of host vehicle and road environment ahead of the host vehicle and determines an effective objective vehicle. The decision layer determines the control commands of longitudinal dynamics, such as the desired acceleration, based on the information provided by the information Fperception layer. The control layer tracks the control commands from the decision layer based on the longitudinal dynamics of the host vehicle. Besides the three layers, the acceleration estimation block is added to observe the accelerations of preceding vehicle and host one.

In existing literatures, drivers' characteristics are drawn into the design of decision layer, such as driving safety, energy economy and so on. However, the foreseeability of drivers, which is represented with the preceding vehicle acceleration that is regarded as a constant or external disturbance, has seldom been studied. In view of this, a effective way is to add a feedforward term of preceding vehicle acceleration into the headway control algorithm. In the Section, an inter-vehicle kinematic is modelled and the multi performance indicators are quantized with states and control input of the model. The accelerations of preceding vehicle and host one are estimated via a differential tracker. The decision of desired acceleration is transformed into a design of feedforward and feedback controller with state and control constraints.

2.1. Model of inter-vehicle kinematic

One of the desired inter-vehicle distance models, constant time gap policy is indicated as follows

$$d_{des} = t_g v_f + d_0 \tag{1}$$

where, d_{des} is the desired inter-vehicle distance, v_f is the speed of ACC vehicle, t_g and d_0 are the time gap and the minimum safe inter-vehicle distance, respectively.

Considering the delay of the control layer and longitudinal dynamics of host vehicle, that is , the delay of acceleration a_f tracking the desired acceleration a_{des} , a first-order inertial system is established as (Naus et al., 2010)

$$\dot{a}_f = \frac{1}{T}(-a_f + a_{des}) \tag{2}$$

where, T is the delay (Rajamani & Shladover, 2001), T =0.45 s.

Define inter-vehicle distance d , the inter-vehicle distance error is $\Delta d = d - d_{des}$; relative velocity $\Delta v = v_p - v_f$, where, v_p is the speed of preceding vehicle. It is assumed that the objective ahead can be effectively detected, that is, d and Δv can be provided from the information perception layer directly. Combine the formulas above to derive

$$\dot{x}(t) = Ax(t) + Bu(t) + Ea_p(t) \tag{3}$$

where, $x(t) = \begin{bmatrix} \Delta d & \Delta v & a_f \end{bmatrix}^T$, $u(t) = a_{des}$, $a_p(t)$ is the preceding vehicle acceleration.

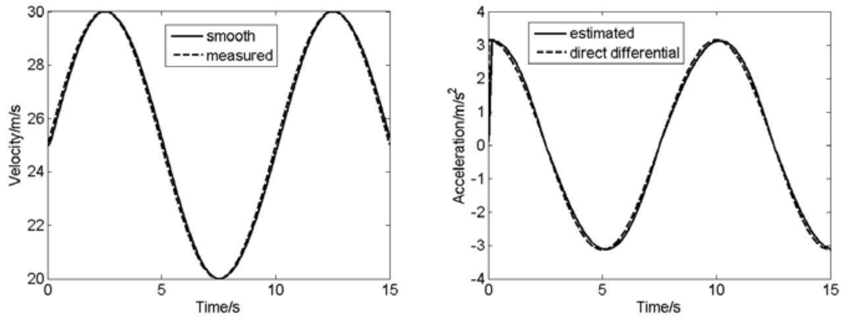


Fig. 2: The results of differential tracker

$$A(t_g)=\begin{bmatrix}0 & 1 & -t_g\\ 0 & 0 & -1\\ 0 & 0 & -1/T\end{bmatrix},\quad B=\begin{bmatrix}0\\ 0\\ 1/T\end{bmatrix},\quad E=\begin{bmatrix}0\\ 1\\ 0\end{bmatrix}.$$

In the model, t_g and T are constants. If t_g is tuned by a driver, the model is a time-varying one. This will be studied in our future work, too.

The jerk is defined as

$$j(t)=\dot{a}_f(t)\,.$$

2.2. Acceleration estimation

$a_f(t)$ and $a_p(t)$ are unavailable generally, a good control performance can be obtained by estimating them correctly. If a direct differentiation of velocity is applied, then the measurement noise is enlarged, and a pulse signal with a large magnitude may be gained and the actuators may be damaged while the signal is jumping (such as step signal). A low-pass filter is added on the basis of direct differentiation. This leads to a phase lag. To obtain a smooth and correct differential signal, a nonlinear differential tracker is applied (Han & Wang, 1994). It is indicated as follows

$$\begin{cases}x_1(k+1)=x_1(k)+Tx_2(k)\\ x_2(k+1)=x_2(k)-sat(g(k),RT)\end{cases}$$

$$\delta=RT^2$$

$$z(k)=x_1(k)-r(k)+Tx_2(k)$$

$$g(k)=\begin{cases}x_2(k)+\dfrac{z(k)}{T},|z(k)|<\delta\\[2ex] x_2(k)-\dfrac{R}{2}sign(z(k))(T-\sqrt{T^2+\dfrac{8|z(k)|}{R}}),|z(k)|>\delta\end{cases}$$

where, $r(k)=v_p(t)=\Delta v(t)+v_f(t)$, $x_1(k)$ and $x_2(k)$ are the smooth preceding velocity signal and the estimated preceding vehicle acceleration, respectively. T is the sampling time, R is the tracker parameter, which determines the tracking speed and the result of smooth filter.

Let $R=20$ and $T=0.01s$, take the sine curve of preceding vehicle speed for example. The effectiveness of the algorithm is validated as shown in Figure 2.

2.3. Quantization of multi performance indicators

In this Section, $\Delta d,\Delta v$, j and a_f,u are used to represent safety, comfort and economy. From the optimizing control theory perspective, the weights of the states reflect the importance of corresponding performance indicator. For instance, the larger the weight of j, the more important of comfort in existing operating condition. However, the determination of initial value of weight and the weight of corresponding indicator in different operating condition are difficulties. In our work, the determination of weights for indicators is transformed into the design of constraints of indicators. ‘tight’ and ‘loose’ of constraints corresponds to ‘large’ and ‘small’ of weights.

After quantization of the indicators, the constraints of indicators are represented as inequalities.

Driving safety: $|\Delta d| \le \Delta d_m$, $|\Delta v| \le \Delta v_m$;

Energy economy: $|a_f| \le a_{fm}$;

Passenger comfort: $|j| \le j_m$.

Passengers have a obvious feeling if the absolute value of jerk exceeds 2m/s^3 (Yi &Chung, 2001).

Normal driving set: a polyhedron defined with the bounds of states of the model, that is,

$\Re(Z^N) = \left\{ x \in R^3 : \left| Z^N(i)x \right| \le 1 \right\}$,

where, $Z^N \in R^{3\times3}$ is a diagonal matrix, $Z^N(1,1) = 1/\Delta d_m$, $Z^N(2,2) = 1/\Delta v_m$, $Z^N(3,3) = 1/a_{fm}$, $Z^N(i), i = 1,2,3$ are rows of the diagonal matrix. The initial states $x_0 \in \Re(Z^N)$.

2.4. Structure of headway controller

To reflect foreseeability of drivers to the effective objective ahead in the design of ACC, a controller structure of feedforward and feedback is derived

$$u(t) = Kx(t) + Fa_p(t) \tag{4}$$

where, K and F are the feedforward and feedback controller gains to be designed, respectively.

Then,

$$\begin{aligned} j(t) &= -\frac{1}{T}\begin{bmatrix}0 & 0 & 1\end{bmatrix} x(t) + \frac{1}{T}Kx(t) + \frac{1}{T}Fa_p(t) \\ &= \frac{1}{T}(K - D)x(t) + \frac{1}{T}Fa_p(t) . \end{aligned}$$

The longitudinal of preceding vehicle can be written as

$a_p(t) = a_{pm} r(t)$,

where, $r(t)$ is the reference input, $|r(t)| \le 1$, a_{pm} is the maximum of the preceding vehicle acceleration.

Combine (3) and (4) to derive the closed-loop system

$$\dot{x}(t) = \tilde{A}x(t) + \tilde{B}r(t) \tag{5}$$

in which, $\tilde{A} = A + BK$, $\tilde{B} = a_{pm}(E + BF)$.

In summary, the decision of the desired acceleration is transformed into the design of a feedforward and feedback controller with state and control constraints. As Figure 3 shows, the controller contains two parts: feedback controller and feedforward one. The feedback controller corrects error of states in real time and computes the desired acceleration precisely. The feedforward controller compensates the influence of preceding vehicle acceleration on following performance and thus improves the foreseeability of ACC effectively.

As shown in Figure 4, The states constraints constitutes automotive normal driving set $\Re$. Automotive reachable set is defined as a set that all of the reachable states proceed from the initial states in $\Re$ at some time and take over all the control inputs in the control constraint set. The main thought of the feedforward and feedback controller is to find a control law to minimize the reachable set with bounded preceding vehicle acceleration for initial states in $\Re$ .Equations.

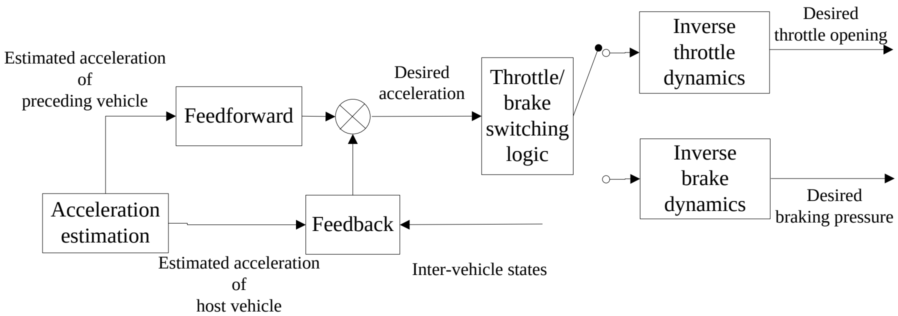


Fig. 3. Feedforward + feedback headway controller

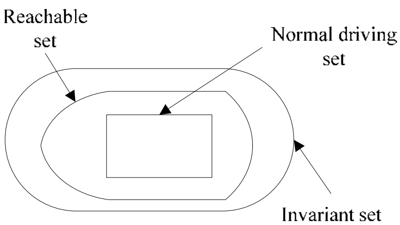


Fig. 4. Normal driving set, reachable set and ivariant set for two dimensional state space($\begin{bmatrix}\Delta d & \Delta v\end{bmatrix}^T$)

3. Design of headway control algorithm

As stated before, Multi performance indicators are quantized with states and control input and the zone of the indicators are represented with states and control constraints. The decision of desired acceleration has been transformed into the design of headway control algorithm with states and control constraints.

The states are stabilized into an ellipsoid invariant set determined with a common Lyapunov function via quadratic boundedness theory. To achieve this, a minimum invariant set including reachable set needs to be found out. The invariant set has an appearance of ellipsoid $\varepsilon(P)$. Where, Lyapunov matrix $P = P^T > 0$, which satisfied $\varepsilon(P) = \left\{\tilde{x} \in R^8 : \tilde{x}^T P \tilde{x} \le 1\right\}$, $\Re \subset \varepsilon(P)$ (see Figure 4). According to quadratic boundedness theory, if common Lyapunov function $V(x(t)) = x^T(t)Px(t)$ exists, then $|r(t)| \le 1$, $V(x(t) \ge 1$, $\dot{V}(x(t)) < 0$ (Ding, 2009; Alessandri et al., 2004). Let $Q = P^{-1}$, $Y = KQ$, and apply Schur complement lemma to derive

$$\begin{bmatrix} AQ + BY + (*) + \alpha Q & a_{pm}(E + BF) \\ * & -\alpha \end{bmatrix} \le 0.$$

To improve following performance, a minimum reachable set corresponding to initial states in normal driving set should be found. Thus, normal driving set should be included in ellipsoid invariant set, which shoule be minimized. The inclusion corresponds to matrix inequalities as follows

$$\begin{bmatrix} 1 & \left(z_i^N\right)^T \\ * & Q \end{bmatrix} \ge 0, i = 1,2,3,4$$

where, $z_i^N, i = 1,2,3,4$ is a half vertexes of polyhedron. $z_1^N = \begin{bmatrix}\Delta d_m & \Delta v_m & a_m\end{bmatrix}^T$, $z_2^N = \begin{bmatrix}\Delta d_m & \Delta v_m & -a_m\end{bmatrix}^T$, $z_3^N = \begin{bmatrix}\Delta d_m & -\Delta v_m & a_m\end{bmatrix}^T$, $z_4^N = \begin{bmatrix}\Delta d_m & -\Delta v_m & -a_m\end{bmatrix}^T$.

Define set $\varepsilon(P) \subset \Re(K,F) = \left\{ x \in R^3 : \left| Kx + Fa_p \right| \le u_m \right\}$.

Constrain invariant set in the set $\Re(K,F)$ and bounded control input is derived. The following inequalities are gained.

$$\begin{cases} Kx + a_{pm}Fr + u_m \ge 0 \\ -Kx - a_{pm}Fr + u_m \ge 0 \end{cases}$$
$$\forall x \in R^3, x^T Px \le 1; \quad \forall r \in R, |r| \le 1$$

Rewrite them as matrix inequalities to derive

$$\begin{bmatrix} x(t) \\ w(t) \\ 1 \end{bmatrix}^T \begin{bmatrix} 0 & 0 & -\frac{1}{2}K^T \\ 0 & 0 & -\frac{1}{2}a_{pm}F \\ -\frac{1}{2}K & -\frac{1}{2}a_{pm}F & u_m \end{bmatrix} \begin{bmatrix} x(t) \\ w(t) \\ 1 \end{bmatrix} \ge 0$$

$$\begin{bmatrix} x(t) \\ w(t) \\ 1 \end{bmatrix}^T \begin{bmatrix} 0 & 0 & \frac{1}{2}K^T \\ 0 & 0 & \frac{1}{2}a_{pm}F \\ \frac{1}{2}K & \frac{1}{2}a_{pm}F & u_m \end{bmatrix} \begin{bmatrix} x(t) \\ w(t) \\ 1 \end{bmatrix} \ge 0 .$$

For $\forall x \in R^3, \forall r \in R$,

$$\begin{bmatrix} x(t) \\ w(t) \\ 1 \end{bmatrix}^T \begin{bmatrix} -P & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x(t) \\ w(t) \\ 1 \end{bmatrix} \ge 0$$

$$\begin{bmatrix} x(t) \\ w(t) \\ 1 \end{bmatrix}^T \begin{bmatrix} 0 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x(t) \\ w(t) \\ 1 \end{bmatrix} \ge 0$$

Apply S-procedure to derive the efficient and sufficient conditions of above inequalities. In the above inequalities, the sum of feedback term and feedforward term is bounded. However, the situation that the terms are large and the signs of them are different is not dealt with. Thus the following constraints are added.

$$|Kx(t)| \le u_m$$
$$|Fa_p(t)| \le u_m$$

Rewrite them into matrix inequalities to derive

$$\begin{bmatrix} 1 & \frac{1}{u_m}Y \\ * & Q \end{bmatrix} \geq 0,$$
$$-u_m \leq Fa_{pm} \leq u_m.$$

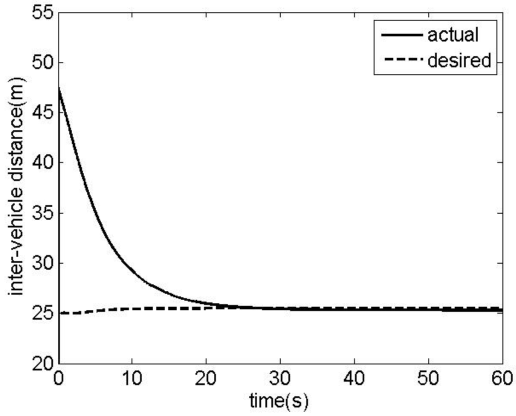
In the same way, matrix inequalities corresponding to comfort constraints can be derived. In the manuscript, the preceding vehicle acceleration is assumed to be provided by dynamics simulation software directly. The foreseeability will be simulated by estimating accelerations of host vehicle and preceding one in our future work.

4. Simulations

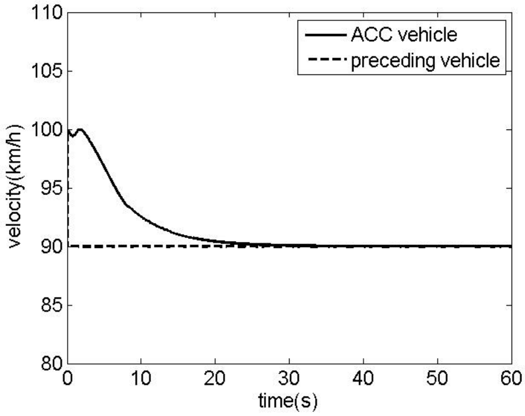
In this Section, the designed headway control algorithm is validated in two operating conditions: constant preceding vehicle velocity and changing preceding vehicle velocity. The headway control algorithm, information perception layer and control layer (throttle and brake inverse longitudinal dynamics models [10] are established in Matlab/Simulink software. Dynamics model of a domestic passenger car is developed in vehicle dynamics simulation software.

4.1. Constant speed of preceding vehicle

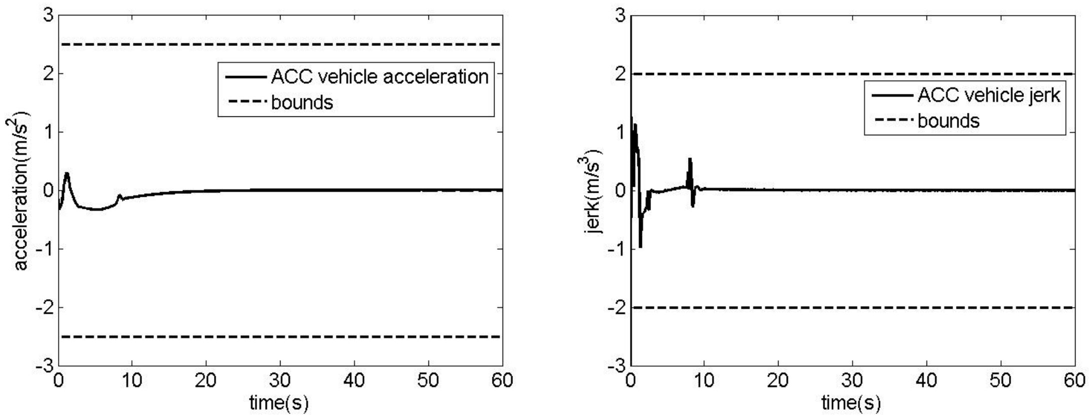
In this simulation, the speed of preceding vehicle is constant as 90 km/h. The initial speed of host vehicle is 100 km/h and the initial inter-vehicle distance is 47 m. As shown in Figure 5(a-b), the actual inter-vehicle distance and speed of ACC vehicle converge asymptotically to the desired inter-vehicle distance and the speed of preceding vehicle, respectively. The ACC vehicle enters into steady following mode after about 20 s. In the transient stage, as Figure 5(c-d) shows, the acceleration and jerk are in the preset constraint bounds. Thus, the energy economy and passenger comfort are guaranteed.



(a)



(b)



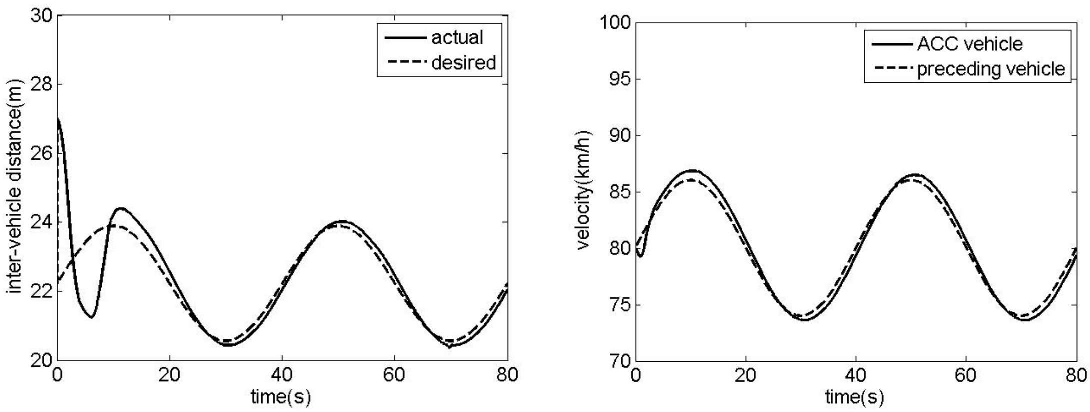
(c) (d)

Fig. 5: Constant velocity of preceding vehicle

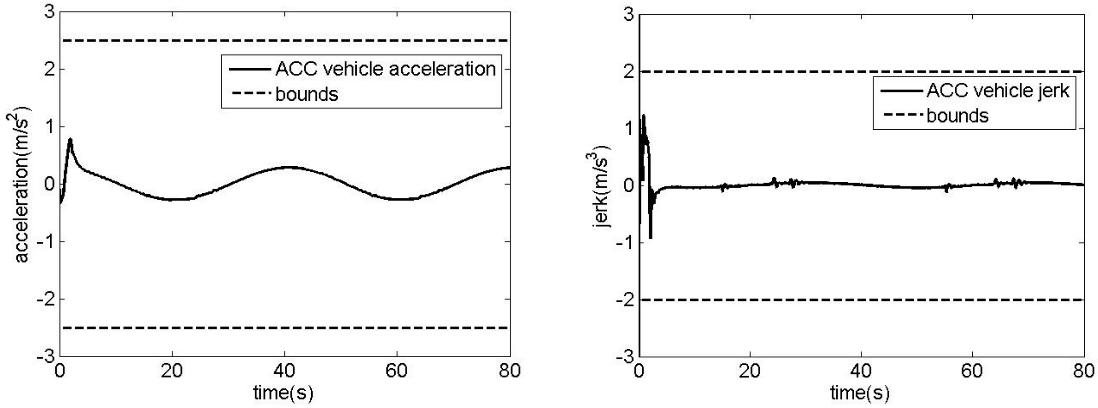
4.2. Changing speed of preceding vehicle

Furthermore, to verify the designed algorithm overcoming the changing preceding vehicle acceleration, a simulation under the following operating condition will proceed. The initial velocities of ACC vehicle and preceding vehicle are 80 km/h. The initial inter-vehicle distance between host vehicle and preceding one is 27 m. Thus, the host vehicle is in steady following mode initially. The speed of preceding vehicle changes with a form of sinusoid as the dotted line shown in Figure 6(b).

As shown in Figure 6(b), the speed of host vehicle tracks that of preceding vehicle stably with a little delay. The actual inter-vehicle distance tracks the desired one steadily with a error in the preset constraint bounds. Thus, the driving safety is guaranteed. From Figure 6(c-d), the maximum of acceleration and jerk do not exceed the comfort and economy constraint bounds. Thus, the designed algorithm is valid overcoming the changing velocity of preceding vehicle.



(a) (b)



(c) (d)

Fig. 6: Changing velocity of preceding vehicle

5. Conclusions

A human imitating headway control algorithm coordinating multi performance indicators is designed under feedforward and feedback control framework via quadratic boundedness concept. The multi performance indicators are quantized with states and control input of inter-vehicle kinematic model. The bounds of indicators are represented with states and control constraints and then are transformed into linear matrix inequalities. Under feedforward and feedback control framework, the designed headway control algorithm reflects human drivers' following behaviour by coordinating the multi performance indicators and foreseeability via a feedforward controller. The simulation results show that the indicators are located in the preset constraint bounds in various operating conditions. Thus, the acceptability and practicability of ACC are improved.

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